The Physical Connection and Magnetic Coupling of the MICE Cooling Channel Magnets and the Magnet Forces for Various MICE Operating Modes *

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***Abstract*— A key issue in the construction of the MICE cooling channel is the magnetic forces between various elements in the cooling channel and the detector magnets. This report describes how the MICE cooling channel magnets are hooked to together so that the longitudinal magnetic forces within the cooling channel can be effectively connected to the base of the experiment. This report presents a magnetic force and stress analysis for the MICE cooling channel magnets, even when longitudinal magnetic forces as large as 700 kN (70 tons) are applied to the vacuum vessel of various magnets within the MICE channel. This report also shows that the detector magnets can be effectively separated from the central MICE cooling channel magnets without damage to either type of magnet component.**

***Index Terms*—Superconducting Solenoids, and Magnetic Force**

I. Introduction

The development of a muon collider or a neutrino factory requires that beams of low emittance muons be produced. A key to the production of low emittance muons is muon cooling. A demonstration of muon cooling is essential to the development of muon accelerators and storage rings [1]. The international Muon Ionization Cooling Experiment (MICE) will be demonstrate of muon cooling in a configuration of superconducting magnets that may be useful for a future neutrino factory [2].

Ionization cooling of muons means that muons have their momentum reduced in both the longitudinal direction and the transverse direction by passing them through a low Z absorber. RF cavities are then used to re-accelerate the muons to their original momentum. If the transverse momentum is lower after the muons have been re-accelerated, cooling has been achieved.

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The central section of MICE cools the muons in low Z absorbers, and re-acceleration of the muons occurs in RF cavities that are between the absorbers. At the ends of the MICE channel are solenoids that match the beam to the cooling section and provide a uniform magnetic field (4.00 ±0.02 T over a length of 1.0 m and a diameter of 0.3 m) [3]. Within the uniform field section are five planes of scintillating fibers that are used to measure the beam emittance entering and leaving the central cooling channel.

II. The MICE Cooling Channel Magnets

The MICE will test cooling on a low intensity muon beam from the ISIS ring at the Rutherford Appleton Laboratory in the United Kingdom. Dipping a metal target into the ISIS proton beam will produce pions. These Pions will decay into a muon beam within a superconducting pion decay solenoid. This solenoid is well up stream from the MICE channel magnets. The muon beam is directed to the MICE channel through a beam line that uses conventional iron dominated quadrupole magnets. The muon beam enters the experiment after passing through a diffuser that will scatter the muons to produce a beam of desired emittance. At this point the muon beam enters the MICE channel, with its superconducting solenoids.

A schematic of the MICE channel is shown in Figure 1. The MICE channel consists of eighteen superconducting solenoid coils that are contained in seven modules. Figure 2 shows the MICE channel with its seven magnet modules. The central part of the MICE channel contains five of the seven modules. At the ends of the central cooling channel are the two tracker modules that are each 2923 mm long [3]. The final configuration of the central cooling section of the MICE channel will consist of three absorber focus coil modules (AFC modules) and two RF coupling coil modules (RFCC modules). The 1906-mm long RFCC modules [4] separate the three 844-mm long AFC modules [5]. The total MICE channel length is 12.19 meters, excluding the two iron shields and the detectors at the ends of the channel.

Each tracker magnet consists of five coils mounted into a single cold mass assembly. Each AFC module contains two superconducting coils mounted into the cold mass assembly. The RFCC module has a single coupling coil mounted in its own cryostat, which is attached to the outside surface of the vacuum vessel that contains four 201 MHz RF cavities.

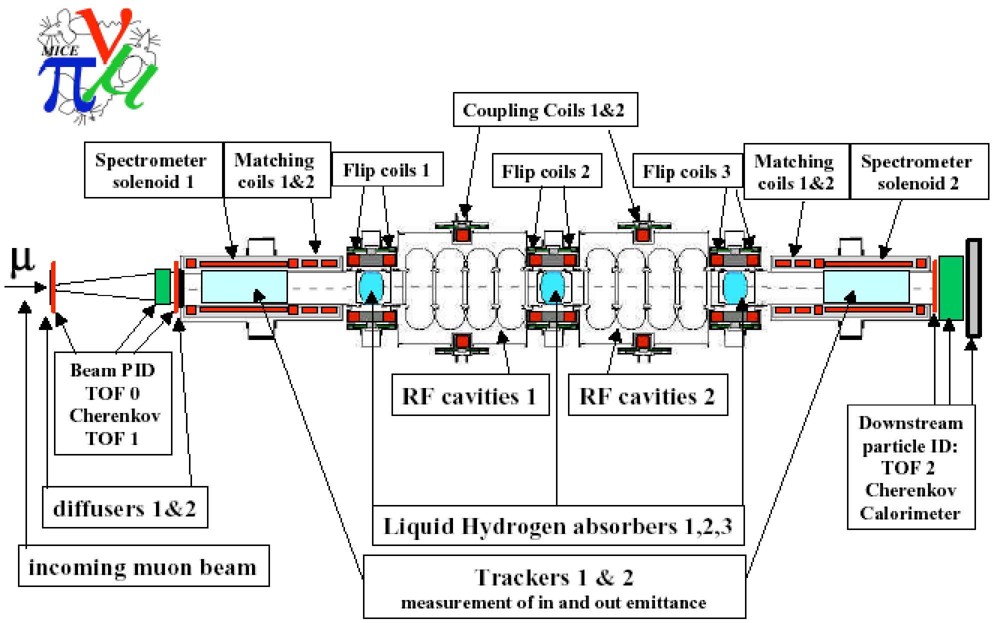

Figure. 1. A Cross-section Representation of MICE. The tracker magnet is a combination of two matching coils plus a three–coil spectrometer solenoid that is around the tracker. Not shown are the iron shields at the tracker magnet ends. The AFC module is described as flip coils, even though the polarity of the coils in the AFC module may be either in the flip or non-flip mode. The coupling coils are around the RF cavities in the RFCC module.

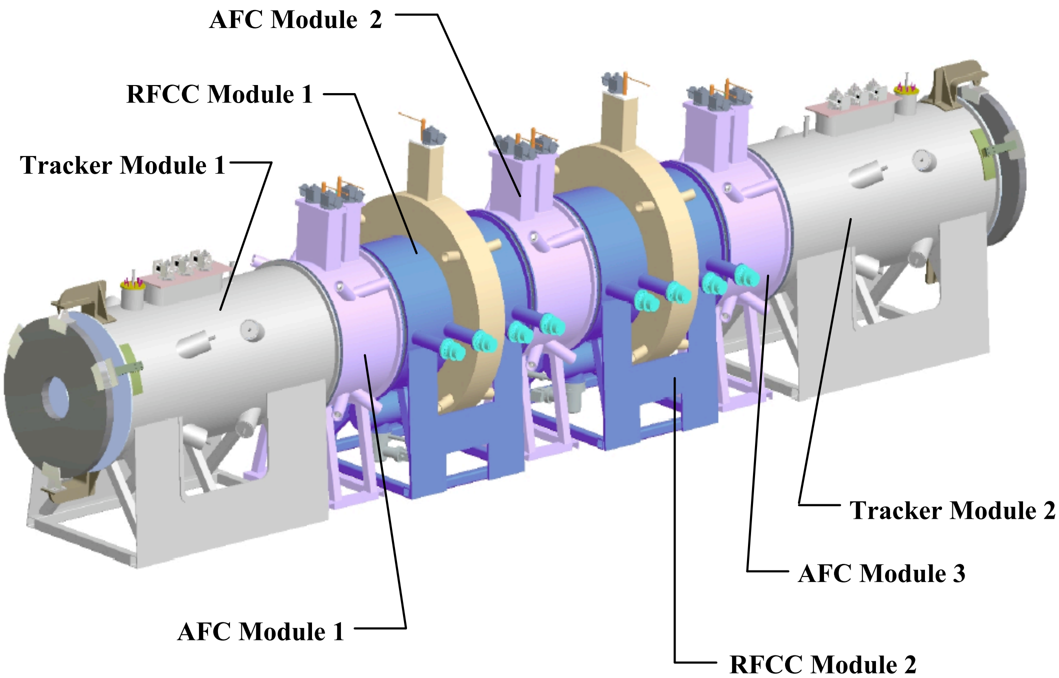

Figure. 2. A Three Dimensional Schematic Representation of the MICE Channel with three AFC modules and two RFCC modules

III. The Magnetic Coupling of the MICE Coils

Since there are no iron shields to shield the coils and return the flux, the eighteen MICE coils are coupled together magnetically. Tables 1 and 2 present the inductance matrices for circuits **S**, **M2**, **M1**, **F**, **C1** and **C2** in the flip and non-flip modes [6]. The coils in the three AFC modules are connected in series to form circuit **F**. Coupling coils **C1** and **C2** are individually powered. The end coils and center coil of the tracker spectrometer magnet are connected in series and in series with the same coils at the other end of the channel forming circuit **S**. Each match coil in the tracker solenoid is connected in series with the corresponding match coil in the tracker module at the opposite end of the MICE channel forming circuits **M1** and **M2**. The MICE channel may be operated in the flip mode (with each AFC magnet in the gradient mode) or it may be operated in the non-flip mode (with each solenoid in the solenoid mode). Two semi flip modes are also possible with the center AFC magnet flipped or the two end AFC magnets flipped.

TABLE 1. THE INDUCTANCE MAP FOR THE MICE MAGNET CIRCUITS IN THE FLIP MODE

	S	**M2**	**M1**	**F**	**C1**	**C2**
S	**153.8**	1.603	0.705	0.188	0.547	0.547
M2	1.603	**10.70**	1.003	0.151	0.165	0.165
M1	0.705	1.003	**25.89**	1.152	0.439	0.439
F	0.188	0.151	1.152	**304.4**	5.569	5.569
C1	0.547	0.165	0.439	5.569	**563.0**	6.713
C2	0.547	0.165	0.439	5.569	6.713	**563.0**

TABLE 2. THE INDUCTANCE MAP FOR THE MICE MAGNET CIRCUITS IN THE NON-FLIP MODE

	S	**M2**	**M1**	**F**	**C1**	**C2**
S	**154.5**	1.605	0.715	0.699	0.807	0.807
M2	1.605	**10.90**	1.003	0.344	0.199	0.199
M1	0.715	1.003	**26.11**	1.812	0.628	0.628
F	0.699	0.344	1.812	**416.3**	17.91	17.91
C1	0.807	0.199	0.628	17.91	**563.0**	6.713
C2	0.807	0.199	0.628	17.91	6.713	**563.0**

Table 1 presents the inductance matrix for the magnets when MICE is operated in the flip mode. Table 2 presents the inductance matrix for the magnets when MICE is operated in the non-flip mode. There can be other tables with more terms that can be used to describe the inductance matrices for the two possible semi-flip modes for MICE. The bold numbers in the diagonal from the upper left corner to the lower left corner of Tables 1 and 2 are the self-inductances for the circuits. The non-diagonal terms are mutual inductances between various circuits. All inductances in Tables 1 and 2 are given in henries.

The fact that there are large mutual-inductance terms in Tables 1 and 2 illustrates that there is coupling between the various magnet circuits that make up MICE. The coupling between the various magnet circuits manifests itself in how the magnets are affected during a quench and the fact the quenching of one group of magnets in MICE will cause adjacent magnets to quench [6].

The inductive coupling between coils also causes the forces between coils in a magnet module and it causes forces between various modules in MICE. The forces between the coils within magnet modules are carried by the structure of the cold mass assembly. An example is the large forces in the AFC magnet when it is operated in the flip mode. Inter-coil forces can be as high as 3.53 MN forcing the coils apart in that module when it operates at its highest current in the flip mode. The AFC magnet inter-coil force is carried by the mandrel and the magnet cover plates.

The forces between modules must be carried to the room temperature part of the module through the cold mass support system. These forces are directly related to the mutual inductances in tables 1 and 2. The forces that are transmitted to room temperature must be carried to the base plate or to another magnet through the module vacuum vessel and stand.

TABLE 3. MODULE COLD MASS SUPPORT FORCES (TONS) FOR THE BASELINE CASE AND THE FLIP AND NON-FLIP 240 MEV/C CASES

Module	Baseline	240 MeV/c Flip	240 MeV/c Non-flip
Tracker 1	25.5	27.2	24.5
AFC1	-18.8	-26.3	-13.0
RFCC1	-8.8	-12.7	-6.2
AFC2	0	0	0
RFCC2	+8.8	+12.7	+6.2
AFC3	+18.8	+26.3	+13.0
Tracker 2	-25.5	-27.2	-24.5

TABLE 4. MODULE COLD MASS FORCES (TONS) FOR VARIOUS MAGNET MODULE QUENCH MODES (FLIP MODE @ 240 MEV/C)

Module	Both Trackers	Coupling C1	Three AFC
Tracker 1	**0**	+42.6	-14.7
AFC1	+30.8	-48.4	**0**
RFCC1	-21.9	**0**	-8.7
AFC2	0	+31.0	**0**
RFCC2	+21.9	-10.2	+8.7
AFC3	-30.8	+26.0	**0**
Tracker 2	**0**	-41.0	+14.7

IV. MAGNETIC FORCES ON THE MAGNET MODULES

The magnetic force on a magnet coil is proportional to the magnetic induction on the coil from the currents in the other coils and the total current in the coil. The force that is applied to the cold mass support system for a magnet module is the sum of the forces on the coils within that module. The net mass support force is predominately longitudinal [7]. The net radial and azamuthal magnetic forces on the cold mass in a magnet module are small by virtue of symmetry. (The dominant radial force is due to gravity.)

Table 3 shows the longitudinal magnetic forces on the various magnet modules for the baseline case (p = 200 MeV/c □ = 420 mm in the flip mode), the flip mode case at p = 240 MeV/c □ = 420 mm, and the non-flip mode for p = 240 MeV/c □ = 420 mm. The module magnetic forces will always be higher for the flip mode than the non-flip mode (despite slightly better coupling) because the currents in most of the coils are higher. Thus in normal operation the longitudinal forces are highest for the flip mode.

Table 4 shows the longitudinal magnetic forces on the cold mass due to quenching of coils in both tracker modules, due to quenching of a single coupling coil, and the quenching of the three focusing coils. It is expected that a quench of one of the coils in a tracker magnet will quench all coils in the tracker magnet. A quench in one tracker magnet will cause both tracker magnets to quench, because they are in series. Likewise because the AFC magnets are in series, a quench in one AFC magnet will cause all of them to quench. The worst-case cold mass support forces during a quench will occur when a coupling coil quenches at 240 MeV/c in the flip mode. This case determines the design force for the tracker magnet cold mass support system, which is set at 50 tons.

TABLE 5. MODULE COLD MASS SUPPORT FORCES FOR LEAD REVERSAL IN THE AFC AND COUPLING MAGNETS (FLIP MODE @ 240 MEV/C)

Module	AFC Reversed	Coil C1 Reversed	C1 and C2 Reversed
Tracker 1	-11.8	+25.8	+25.8
AFC1	**+3.6**	-65.7	-65.7
RFCC1	-20.3	**+22.5**	**+15.6**
AFC2	**0**	+61.9	0
RFCC2	+20.3	-38.6	**-15.6**
AFC3	**-3.6**	+4.3	+65.7
Tracker 2	+11.8	-10.2	-25.8

TABLE 6. MODULE COLD MASS SUPPORT FORCES FOR LEAD REVERSAL IN THE M1, M2 AND THE SPECTROMETER COILS (FLIP MODE @ 240 MEV/C)

Module	Coil M1 Reversed	Coil M2 Reversed	Spectrometer Reversed
Tracker 1	**-25.6**	**-6.8**	**12.1**
AFC1	+45.6	+2.4	+1.2
RFCC1	18.3	-25.5	-29.9
AFC2	0	0	0
RFCC2	-18.3	+25.5	+29.9
AFC3	-45.6	-2.4	-1.2
Tracker 2	**+25.6**	**+6.8**	**-12.1**

Tables 5 and 6 show the effect of hooking the coils up backward. From Tables 5 and 6, it is clear that the effects of reversing the leads on most of the circuit are relatively benign except when the leads are reversed on one or both coupling coils. These two cases cause large forces on the AFC magnet cold mass supports (up to 65.7 tons). Since the AFC modules are designed to be interchangeable, cold mass support design longitudinal force has been set at 700 kN on all AFC magnets. All of the other magnet modules are designed for a 500 kN force in the longitudinal direction. There is a safety margin of three to four on all magnet cold mass supports.

V. THE TRANSMISSION OF MAGNETIC FORCES BETWEEN THE MAGNET MODULES AND TO THE GROUND

Magnetic forces from the module cold mass supports must be transmitted either to adjacent magnet modules or to the floor. During normal operation of MICE, the deflection within a module cannot exceed 0.5 mm in the center of the module (or less than 1 mm on the upper surface of the module). The longitudinal force must no cause a tilt in the magnet axis by more than 0.7 m-radians. Fig. 2 shows the stands for the three types of modules. Because the AFC module is 0.844 m long and the center of the module is about 1.2 meters off of the floor, this module cannot be expected to carry a large longitudinal force to the floor. As a result, the decision was made that the AFC module must be tied to an adjacent RFCC module or tracker module. Studies on both the RFCC module and the tracker module indicate that large longitudinal forces can be taken by these modules.

MICE will be assembled in six stages. Stages 4 through 6 involve one or more AFC modules. Stage 4 has a single AFC module between the two tracker modules. In stage 4, the AFC module would be attached to one of the tracker modules. Stage 5 has two AFC modules and a RFCC module between the two tracker modules. In stage 5, both AFC modules can be attached to the RFCC module or to the two tracker modules. Stage 6 has three AFC modules and two RFCC modules between the two tracker modules (See Fig. 2.) In stage 6 the AFC modules and RFCC modules would be attached together. The tracker modules can attached to the central section of MICE or not be attached. The design of the tracker module allows the forces on the tracker magnet to be connected to adjacent magnets.

VI. CONCLUDING COMMENTS

The superconducting solenoid magnets in MICE are coupled magnetically. This coupling causes voltages to be induced in adjacent coils due to current changes. The magnetic coupling of the coils means that the currents flowing in one magnet module will induce forces in adjacent magnet modules. These forces are largest when MICE operates in the flip mode (with a polarity reversal at each AFC module) at the highest muon momentum (240 MeV/c).

The design longitudinal force for the magnet module cold mass support system and stand is determined by a quench of the magnet or when there is an accidental reversal of the magnet leads at the power supply. As a result, the coupling and tracker magnets are designed for a 500 kN longitudinal force, and the AFC magnet is designed for 700 kN. The stands of the RFCC module and the tracker module are designed so that both stress and deflection are low when the forces are carried to the floor through the stands.

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DISCLAIMER

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